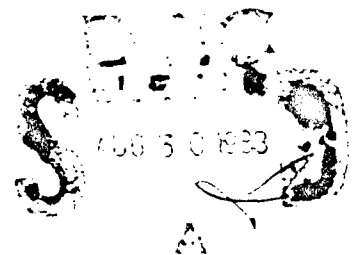EFFECTIVENESS IN REDUCING HEAT STRESS OF THREE CONDITIONED-AIR COOLING

VESTS WORN WITH AND WITHOUT COOLING AIR SUPPLIED TO A FACE PIECE

20030108181

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

FEBRUARY 1983

AD A131975

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER T1/83	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Effectiveness in Reducing Heat Stress of Three Conditioned-Air Cooling Vests Worn With and Without Cooling Air Supplied to a Face Piece		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George F. Fonseca		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Rsch Inst of Env Med Natick, MA 01760		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 3E162777A878 878/AE WU-082
11. CONTROLLING OFFICE NAME AND ADDRESS Same as 9		12. REPORT DATE March 1983
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS (II different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLAS
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, If different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side If necessary and identify by block number)

auxiliary cooling; heat transfer and heat stress

20. ABSTRACT (Continue on reverse side If necessary and identify by block number)

The auxiliary cooling provided by three different air-cooled vests and a ventilated XM-29 Face Piece was directly measured on a life-sized, heated, sectional manikin. These air-cooled systems were worn with a combat vehicle crewman (CVC) ensemble with a complete chemical protective (CW) suit. Cooling rates (watts) were determined for both dry (non-sweating) and completely wet (maximal sweating) skin conditions. At low ventilating air flow rates these air-cooled vests provided cooling primarily over the torso surface. Up to 95% of the cooling —

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provided over the torso-arms-legs areas was over the torso. At higher air flows this percentage decreased to 55%. The design of an air-cooled vest can increase the efficiency of cooling of the ventilating air by maximizing the proportion of cooling air that diffuses over the surface of the body and minimizing the proportion of cooling air that exits an air-cooled vest directly through the clothing to the hot environment. Under the experimental conditions of this study the air-ventilated XM-29 Face Piece contributed about 20% to the total cooling.

AD_____

TECHNICAL REPORT

NO.___T1/83___

EFFECTIVENESS IN REDUCING HEAT STRESS OF THREE CONDITIONED-AIR COOLING
VESTS WORN WITH AND WITHOUT COOLING AIR SUPPLIED TO A FACE PIECE

by

George F. Fonseca

Project Reference: March 1983   Series: ME

US ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE
Natick, Massachusetts 01760

FOREWORD

Biophysical studies investigating the merits of various auxiliary cooling systems are in progress to provide a technical basis for selecting an auxiliary cooling system for combat vehicle crewmen. A recently completed study used each of five different water-cooled undergarments to provide temperature controlled cooling to the surface of a life-sized, sectional manikin via a continuous flow of cooling water through their tubing. An alternative to using water-cooled undergarments to provide continuous auxiliary cooling to vehicle crewmen is to use individual, air-cooled systems. These air-cooled systems could be employed either separately or as an adjunct to one or more of the water-cooled undergarments. This study investigates three air-cooled vests that circulate temperature and relative humidity regulated air over the surface of the skin. In about half of these experiments face cooling was provided by supplying cooling air at the inlet of a face piece.

The Project Officer, Joseph Fratantuono, was responsible for the technical work unit under which this stu: was carried out; he supplied the Individual Protection Laboratory (IPL) Air-Cooled Vest #1; Mrs. Mary Ippolitto of IPL, US Army Natick Research and Development Laboratories (NLABS) supplied IPL Air-Cooled Vest #2; a commerical air distribution system (Air-Cooled Vest #3) proposed (and designed) by Hughes Aircraft Inc. for ROLAND crewmen was supplied by Dr. Alex Weisz.

Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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ABSTRACT

The auxiliary cooling provided by three different air-cooled vests and a ventilated XM-29 Face Piece was directly measured on a life-sized, heated, sectional manikin. These air-cooled systems were worn with a combat vehicle crewman (CVC) ensemble with a complete chemical protective (CW) suit. Cooling rates (watts) were determined for both dry (non-sweating) and completely wet (maximal sweating) skin conditions. At low ventilating air flow rates these air-cooled vests provided cooling primarily over the torso surface. Up to 95% of the cooling provided over the torso-arms-legs areas was over the torso. At higher air flows this percentage decreased to 55%. The design of an air-cooled vest can increase the efficiency of cooling of the ventilating air by maximizing the proportion of cooling air that diffuses over the surface of the body and minimizing the proportion of cooling air that exits an air-cooled vest directly through the clothing to the hot environment. Under the experimental conditions of this study the air-ventilated XM-29 Face Piece contributed about 20% to the total cooling.

1. INTRODUCTION

A combat vehicle crewman encapsulated in a closed chemical protective (CW) suit and sitting in a closed hatched, unventilated tank exposed to radiant heat from the sun in a hot desert environment is subjected to an intolerable heat stress condition (3). An earlier auxiliary water-cooled undergarment study (1) investigated the cooling provided over the torso, arms and legs areas, or cooling only over the head and/or torso. Specified areas of the body were cooled, e.g., a water-cooled cap provided cooling only over the head; other body areas did not receive any cooling. One of these liquid cooling systems (a water-cooled vest) built by Natick Research and Development Laboratories (NLABS) and the Mobility Equipment Research & Development Command (MERADCOM) was evaluated at Yuma Proving Ground, AZ (4). Toner (9) demonstrated that one sign of severe heat stress on a crewman, the convergence of mean weighted skin temperature on the rectal temperature (7), was substantially alleviated by wearing this water-cooled vest. Another recent chamber study (8) compared an Individual Protection Laboratory (IPL) air-cooled vest with a water-cooled vest. This study concluded that this air-cooled vest could be used with the same efficiency as this water-cooled vest.

Continuing the systematic program of the Biophysics Branch of the Military Ergonomics Division at USARIEM of assessing a variety of auxiliary cooling undergarments and supporting equipment, three air-cooled undergarments were investigated. Air-cooled undergarments have been studied since about the 1950's when Mauch (5) designed his Mauch suit. These types of auxiliary cooling undergarments rely almost completely on a body's ability to continuously produce sweat. The evaporation of this sweat from the surface of the skin provides the required cooling to the body. So long as a body is capable of producing sweat, air-cooled undergarments can provide a high rate of cooling

over those areas of the body that receive cooling air from an air-cooled undergarment. This cooling air can not only cool the surface of the skin in the immediate vicinity of the inlet ports in the air-cooled undergarment but could also provide cooling to other areas of the body as this air passes over these areas on its path through the clothing to the hot environment. However, that portion of the cooling air that passes directly from the air-cooled undergarment to the hot environment without passing over the surface of the skin has comparatively little potential for providing cooling to a body. In some of the experiments air-cooling was also provided over the face via a hose connection to an XM-29 Face Piece.

2. EXPERIMENTAL METHOD

The electrically heated sectional manikin consists of six sections: head, torso, arms, hands, legs and feet. This manikin was placed in a standing position in a large temperature and humidity controlled chamber (chamber dimensions: length 5.8 m, width 3.9 m and height 2.7 m). Chamber environmental conditions were varied over the range 29°C, 85% relative humidity to 52°C, 25% relative humidity; inlet cooling air temperature and relative humidity varied over the range 10°C, 20% relative humidity to 43°C, 14% relative humidity and cooling air flows were varied from 1.5 to 15 ft^{3}/min. The three air-cooled vests used in this study were designated: Individual Protection Laboratory Air-Cooled Vest #1 (IPL ACV #1), an early version; Individual Protection Laboratory Air-Cooled Vest #2 (IPL ACV #2), an updated version of IPL ACV #1; and a commerical model, Air-Cooled Vest #3. In addition to supplying cooling air to each of these three air-cooled vests, cooling air was supplied to the face via the inlet of an XM-29 Face Piece.

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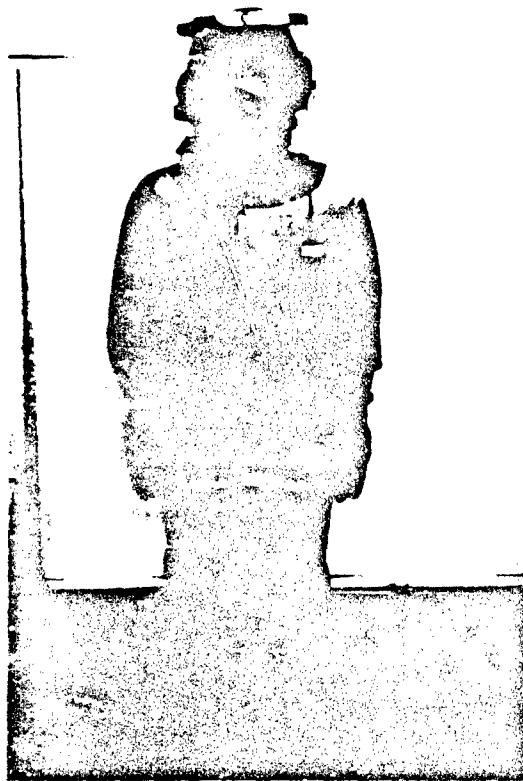
Figure 1.   Photograph of the combat vehicle crewman (CVC) ensemble with the complete chemical protective (CW) suit with an XM-29 Face Piece.

TABLE I

COMPONENTS OF THE COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE AND THE COMPLETE
CHEMICAL PROTECTIVE (CW) SUIT WORN WITH EACH OF THE THREE AIR-COOLED VESTS

Coveralls, Combat Vehicle Crewman

CVC Helmet

Socks, Men's, 40% Cotton, 60% Wool

Black Leather Boots

Suit, Chemical Protective - Coat and Trousers (Overgarment)

XM-29 Face Piece w/Hood

Glove Set, Chemical Protective

Electrical watts supplied to the manikin surface maintained this surface at an average temperature of $35^{\circ}C$. The cooling provided over the torso-arms-legs sections by an air-cooled vest is expressed in terms of cooling rates (watts). Experimentally, these cooling rates are equal to the difference in electrical watts supplied to the torso-arms-legs sections when an air-cooled vest is providing cooling to this manikin surface and when an air-cooled vest is dressed on the manikin but not being supplied with cooling air. Similarly, the head cooling rates (watts) are equal to the difference in electrical watts supplied to the head section when cooling air is being supplied to the XM-29 Face Piece and when cooling air is not being supplied.

Although the two Individual Protection Laboratory air-cooled vests cover only the torso, cooling air from these two air cooled vests can travel over the arms and legs, particularly at the higher ventilating air flows. The air-cooled vest #3 is fabricated to direct cooling air up the back of the neck and down the back and front of each leg. The cooling rates (watts) are therefore given in terms of the cooling provided by these air-cooled undergarments over the surface of the torso-arms-legs. The air cooling provided to the face via a hose connection to the XM-29 Face Piece is given as the cooling rate (watts) over the head. These cooling rates (watts) divided by a calculated value of the maximum cooling potential available in the ventilating air at a given flow rate, inlet air temperature and relative humidity, give an efficiency of cooling for these three air-cooled vests and the XM-29 Face Piece.

The components of the combat vehicle crewman (CVC) ensemble plus a closed chemical protective (CW) suit worn with each of the air-cooled vests are given in Table I. A photograph of this clothing dressed on the manikin is shown in Figure 1.

TABLE II

HEAT TRANSFER PROPERTIES OF THE COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE WORN WITH THE COMPLETE CHEMICAL PROTECTIVE (CW) SUIT

MANIKIN SECTIONS	CLO	i_m	i_m/CLO
HEAD	2.4	.10	.04
TORSO	3.4	.34	.10
TORSO*	4.7	.32	.07
TORSO**	3.4	.31	.09
TORSO***	3.4	.31	.09
ARMS	2.7	.40	.15
HANDS	1.3	.05	.04
LEGS	3.1	.50	.16
FEET	1.6	.18	.11
TOTAL	2.6	.31	.12

*with IPL ACV #1
**with IPL ACV #2
***with ACV #3
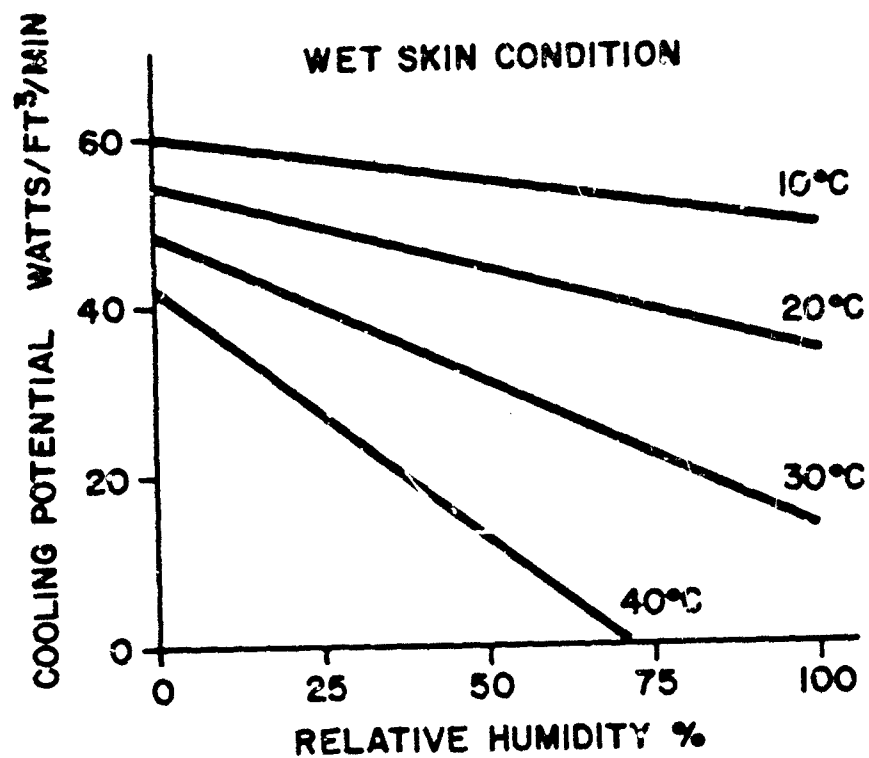
Figure 2.   Cooling potential in watts/ft^3/min as a function of the relative humidity at inlet cooling air temperatures of 10, 20, 30 and 40°C.

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3. RESULTS

A. Heat Transfer Properties of the Combat Vehicle Crewman (CVC) Ensemble Worn with the Closed Chemical Protective (CW) Suit.

The heat transfer properties of the combat vehicle crewman (CVC) ensemble worn with the closed chemical protective (CW) suit are given in Table II. The values of insulation (clo) and evaporative heat transfer coefficient (i_m/clo) presented in this table are used in the calculations of maximal heat transfer rates (watts) for the head, torso, arms and legs areas and the total heat exchanges over all six manikin sections (head, torso, arms, hands, legs and feet). This ensemble worn without a vest would permit about 70W of heat dissipation during exposure to a chamber environment of 29°C, 85% relative humidity. However, with the chamber air temperature increased to 52°C, 25% relative humidity, this ensemble would restrict evaporative heat loss to a greater extent than its restriction of conductive/convective heat gain. In this latter environment, all metabolic heat input to the body would have to be stored in the body and therefore body temperature would continually increase as long as the body was exposed to this hot environment. The tolerance time for sustained work by men wearing this type clothing in such a hot, humid environment is only about 30 minutes (3).

B. Ventilating Air Cooling Potential

The efficiency of cooling for an air-cooled undergarment under various inlet cooling air and environmental conditions may be calculated as the actual cooling provided divided by the maximum cooling potential of the air entering the inlet of an undergarment. This cooling air supplied to the inlet is not returned to a refrigeration unit to be cooled and dehumidified, but rather exits through the clothing to the hot environment. During the passage of this cooling

air over the skin surface the air increases in temperature and moisture content which results in a change in its heat content or enthalpy. When this incoming air becomes moisture saturated at 35°C, this change in enthalpy between the incoming and exiting air is the maximum cooling potential of the cooling air.

The determination of the maximum cooling potential of the ventilating air entering the inlet of an air-cooled vest is the quantity of heat required to raise the inlet air temperature from its initial value to 35°C, and to saturate this air at a temperature of 35°C. The cooling potential, in watts of cooling for each ft^3/min of ventilating air (W/ft^3/min), as a function of the relative humidity of the inlet cooling air at temperatures of 10, 20, 30 and 40°C is given in Figure 2. These curves show that the relative humidity of the inlet cooling air becomes more important with increasing inlet cooling air temperature. For a 10°C inlet cooling air temperature, increasing the relative humidity from 0% to 100% decreases the cooling potential of this ventilating air from about $60W/ft^3$/min to $49W/ft^3$/min or about an 18% decrease. For an inlet cooling air temperature of 20°C, this same increase in relative humidity results in a decrease in cooling potential from $54W/ft^3$/min to $34W/ft^3$/min, or about a 37% decrease. Using the curve for an inlet cooling air temperature of 40°C and a relative humidity value of 10% at a ventilating air flow rate of 10 ft^3/min gives a value for the maximum cooling rate of $36W/ft^3$/min x 10 ft^3/min or 360 watts.

C. Cooling Rates (watts) Provided over the Completely Wet (Maximal Sweating) Skin Surface of the Torso-Arms-Legs Area by the Individual Protection Laboratory (IPL) Air-Cooled Vest (ACV) #1

Cooling rates (watts) for the IPL ACV #1 (shown in Figure 3) are given in Table III for cooling air flow rates of 6, 8 and 10 ft^3/min. Inlet cooling air temperatures were either 10°C at 20% relative humidity or 21°C at 10% relative

humidity. Cooling rates (watts) provided by this IPL ACV #1 over the torso, arms and legs are plotted against the cooling air flow rate in Figure 4. These cooling rates (watts) increase with increasing air flow rate and decreasing inlet cooling air temperature and are dependent upon the particular hot environment in which exposure takes place. Apparently, ventilating air moving from the surface of the skin outward through the clothing does not provide the thermal isolation from a hot environment that a water-cooled undergarment does. An earlier study (1) using water-cooled undergarments showed that they isolated the surface of the skin from a hot environment, i.e., the cooling rates (watts) were independent of the hot environment in which the exposure takes place. With the ACV #1 system, however, less cooling was obtained in a 29°C environment than under comparable conditions in a 52°C environment. Considering all twelve cooling rates (watts) given in Table III, the average percentage difference in the cooling rate (watts) between a 29°C environment and a 52°C environment is about 22%. This result occurs because the ventilating air modifies the temperature gradient existing in the clothing layers for the unventilated condition. Ventilating air at a given temperature and humidity will extract about the same amount of heat from the skin at air temperatures of either 29°C or 52°C. Without ventilation, however, the skin (at 35°C) loses heat to the environment at 29°C but gains heat from the environment at 52°C. Thus the potential for change in heat loss, or what we term cooling, is greater in a 52°C environment. Increasing the ventilating air flow rate from 6 to 10 ft^3/min (a 67% increase) increases the cooling rate (watts) by about 67%, suggesting that over this air flow range, the cooling rate (watts) over the torso-arms-legs area increases in proportion to the ventilating air flow rate.
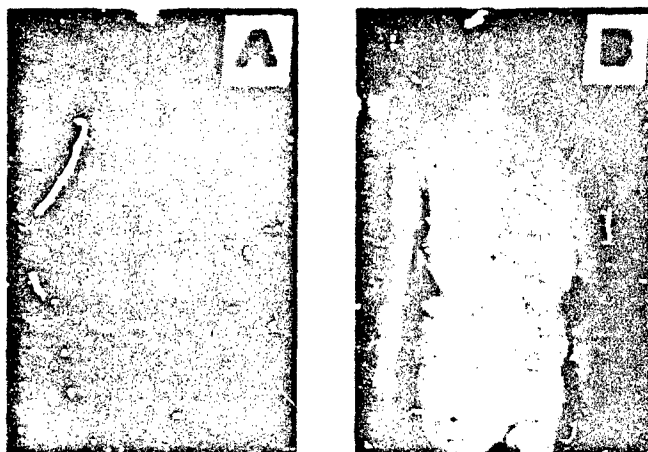
Figure 3.   Photographs of the Individual Protection Laboratory (IPL) Air-
Cooled Vest (ACV) #1: A. Front View, B. Back View.

TABLE III

COOLING RATES (WATTS) PROVIDED BY THE IPL #1 AIR-COOLED VEST

Completely Wet (Maximal Sweating) Skin Surface at 35°C

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY	FLOW RATE (FT³/MIN) AIR-COOLED VEST	COOLING RATES (WATTS) TORSO-ARMS-LEGS	CHAMBER ENVIRONMENTAL CONDITIONS
10°C at 20% RH*	6	95 (15.8)**	29°C at 85% RH
10°C at 20% RH	8	137 (17.1)	29°C at 85% RH
10°C at 20% RH	10	158 (15.8)	29°C at 85% RH
10°C at 20% RH	6	122 (20.3)	52°C at 25% RH
10°C at 20% RH	8	169 (21.1)	52°C at 25% RH
10°C at 20% RH	10	203 (20.3)	52°C at 25% RH
21°C at 10% RH	6	82 (13.7)	29°C at 85% RH
21°C at 10% RH	8	120 (15.0)	29°C at 85% RH
21°C at 10% RH	10	137 (13.7)	29°C at 85% RH
21°C at 10% RH	6	103 (17.2)	52°C at 25% RH
21°C at 10% RH	8	130 (16.2)	52°C at 25% RH
21°C at 10% RH	10	167 (16.7)	52°C at 25% RH

*Relative Humidity
**Watts/Ft³/Min

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TABLE IV

COOLING RATES (WATTS) PROVIDED BY THE IPL ACV #1 WORN WITH A COOLING AIR VENTILATED XM-29 FACE PIECE

Completely Wet (Maximal Sweating) Skin Surface at 35°C

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY	FLOW RATE (FT³/MIN) AIR-COOLED VEST	XM-29 FACE PIECE	COOLING RATES (WATTS) TORSO-ARMS-LEGS	HEAD	TOTAL***	CHAMBER ENVIRONMENTAL CONDITIONS
24°C at 41% RH	3	3	44 (14.7)****	23 (7.7)****	67 (22.4)****	32°C at 26% RH*
32°C at 26% RH	6	NF**	51 (8.5)	0 (0.0)	51 (8.5)	32°C at 26% RH
32°C at 26% RH	15	6.5	142 (9.5)	30 (6.7)	172 (16.2)	49°C at 11% RH
45°C at 14% RH	10	3	76 (7.6)	15 (5.0)	91 (12.6)	49°C at 11% RH

*Relative Humidity
**No Flow
***Sum of Cooling Provided over Head-Torso-Arms-Legs
****Watts/Ft³/Min

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IPL ACV #1
WET SKIN CONDITION

CHAMBER ENVIRONMENT

	AIR TEMP	REL HUMIDITY
	29°C	85%
	52°C	25%

INLET COOLING AIR

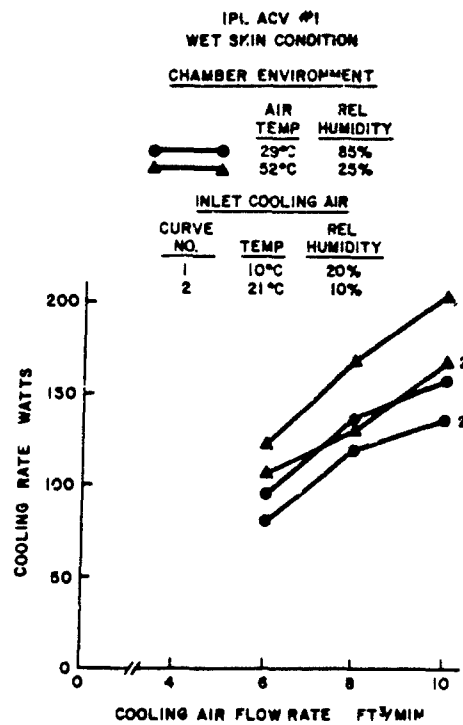| CURVE NO.	TEMP	REL HUMIDITY
1	10°C	20%
2	21°C	10%

Figure 4.   Cooling rates (watts) provided by the IPL ACV #1 over the completely wet (maximal sweating) surface of the torso-arms-legs area as a function of the cooling air flow rate.

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The cooling efficiency of this air-cooled vest (IPL ACV #1) for a completely wet (maximal sweating) skin condition based on the cooling potential of the ventilating air is 28% for exposure to hot environments of 29°C, and 35% for exposure to hot environments of 52°C; the average value of the cooling efficiency of this air-cooled vest is 32%. That is, about 1/3 of the cooling potential of the ventilating air is being utilized when this type of air-cooled vest is worn.

D. Cooling Rates (Watts) Provided by the IPL ACV #1 Worn with the XM-29 Face Piece Over a Completely Wet (Maximal Sweating) Skin Surface

It would appear logical to expect that the cooling air supplied to different areas of a body would initially be at the same air temperature, but could have different air flow rates (e.g., head and torso cooling). Cooling air supplied to the air-cooled vest ranged from 3 to 15 ft^3/min and to the inlet of the XM-29 Face Piece either 3 or 4.5 ft^3/min. Exposure was in two hot environments (air temperature of 32°C at 26% relative humidity and 49°C at 11% relative humidity) and cooling air was supplied to both the IPL ACV #1 and the XM-29 Face Piece at either 24°C at 41% relative humidity, 32°C at 26% relative humidity, or 43°C at 14% relative humidity. These inlet cooling air and environmental conditions were selected for direct comparison with the Air-Cooled Vest #3.

The area of the head is about 29% of the area of the torso. Supplying ventilating air to the inlet connection of an XM-29 Face Piece limits the head area being air cooled to the face region or about 1/3 of the surface area of the head. Cooling air supplied to the torso by an air-cooled vest has the potential to provide cooling over the arms and legs as well as the torso before it exits to a hot environment. Using the cooling rates given in Table IV, the contribution of

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the face cooling to the total cooling rate can be calculated for low (3 ft^3/min) and high (10 and 15 ft^3/min) ventilating air flow rates. At the low air flow rate the face accounts for about 34% of the total cooling rate but the face contribution falls to only about 16% at the higher ventilating air flow rates. However, increasing the air flow does increase face cooling somewhat; this increase may contribute more to the wearer's comfort than a much larger increase in cooling over the rest of the body [6]. The efficiency of cooling of the ventilating air supplied to the face via the inlet connection to the XM-29 Face Piece was about 18%, compared with a cooling efficiency of about 28% for the IPL ACV #1 under these experimental conditions.

E.   Cooling Rates (Watts) Provided Over the Dry (i.e., Non-Sweating) Skin Surface of the Torso-Arms-Legs by the IPL ACV #2

If the cooling provided by conductive/convective heat exchange between the skin surface and the ventilating air is sufficient to maintain the skin dry, then there is no evaporative cooling. For this dry (i.e., non-sweating) skin condition the cooling rates (watts) provided by the IPL ACV #2 (shown in Figure 5) when this vest is supplied with 21°C, 16% relative humidity ventilating air for exposure to a chamber environment of 29°C and 85% relative humidity are given in Table V. Figure 6, a plot of these results, shows that the cooling rate is within 2 watts of being proportional to the ventilating air flow rate; doubling the flow rate from 4 ft^3/min to 8 ft^3/min doubles the cooling rate from 16W to 32W. These cooling rates are equal to the total cooling provided over the torso-arms-legs area. Up to a flow rate of 6 ft^3/min the cooling rate is negligible over the arms and legs. At a flow rate of 10 ft^3/min the cooling rate (watts) over the torso is still providing 88% of the cooling; the arms and legs are providing the other 12%.

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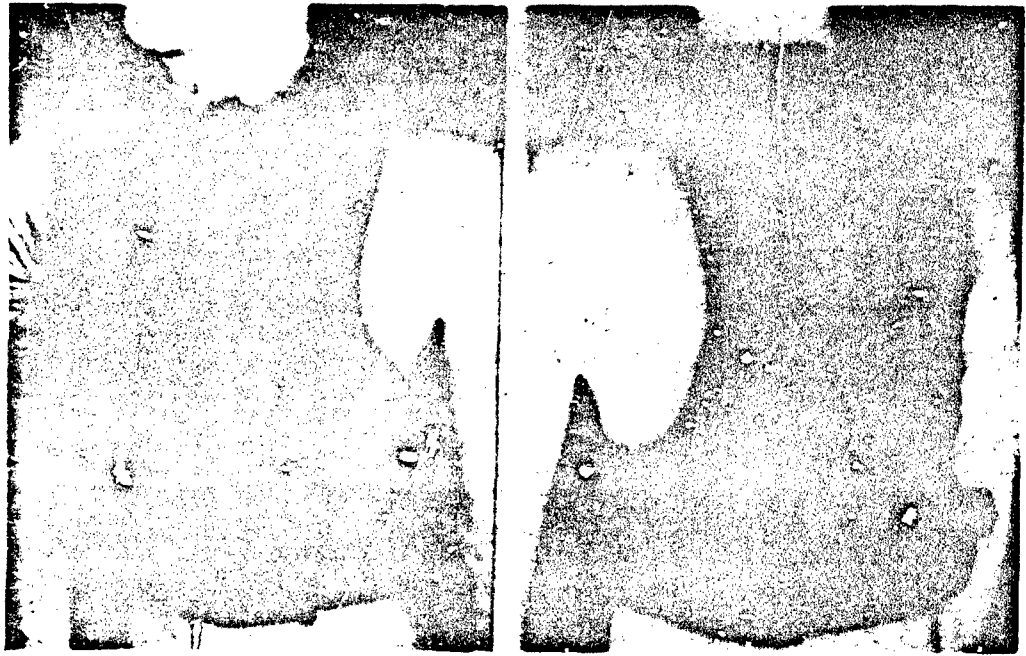
Figure 5.   Photographs of the individual Protection Laboratory (IPL) Air-
Cooled Vest (ACV) #2: A. Front View, B. Back View.

TABLE V

COOLING RATES (WATTS) PROVIDED BY THE IPL ACV #2

for the dry (non-sweating) skin condition

		FLOW RATE (FT^3/MIN)	COOLING RATES	
Chamber Environment:	29°C, 85% rh*	1.5	5	3.3**
		2.0	7	3.5
Cooling Air Inlet		3.0	11	3.7
Environment:	21°C, 16% rh	4.0	16	4.0
		6.0	23	3.8
		8.0	32	4.0
		10.0	38	3.8

*Relative Humidity
**Watts/Ft^3/Min

IPL ACV #2
DRY SKIN CONDITION

CHAMBER ENVIRONMENT		INLET COOLING AIR	
AIR TEMP	REL HUMIDITY	TEMP	REL HUMIDITY
29°C	85%	21°C	16%

Figure 6.   Cooling rates (watts) provided by the IPL ACV #2 over the dry (non-sweating) surface of the torso-arms-legs area as a function of the cooling air flow rate.

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TABLE VI

COOLING RATES (WATTS) PROVIDED BY THE IPL ACV #2

Completely Wet (Maximal Sweating) Skin Surface at 35°C

		FLOW RATE (FT^3/MIN)	COOLING RATES	
Chamber Environment:	29°C at 85% rh*	1.5	58	(38.7)**
Inlet Cooling Air:	21°C at 16% rh	2.0	71	(35.5)
		2.5	81	(32.4)
		4.0	119	(29.8)
		6.0	138	(23.0)
		10.0	212	(21.2)
Chamber Environment:	29°C at 85% rh	1.5	49	(32.7)
Inlet Cooling Air:	21°C at 60% rh	2.2	67	(30.5)
		3.0	72	(24.0)
		4.6	112	(24.3)
		6.0	146	(24.3)
		8.3	177	(21.3)
		10.0	203	(20.3)
Chamber Environment:	52°C at 25% rh	2.2	75	(34.1)
Inlet Cooling Air:	21°C at 16% rh	2.6	79	(30.4)
		6.4	209	(32.7)
		8.0	227	(28.4)
		10.0	254	(25.5)

*Relative Humidity
**Watts/Ft^3/Min

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IPL ACV #2
WET SKIN CONDITION

CHAMBER ENVIRONMENT		CURVE	INLET COOLING AIR	
AIR TEMP	REL HUMIDITY		TEMP	REL HUMIDITY
29°C	65%	●——●	21°C	16%
29°C	85%	■——■	21°C	60%
52°C	25%	▲——▲	21°C	16%

COOLING RATE   WATTS

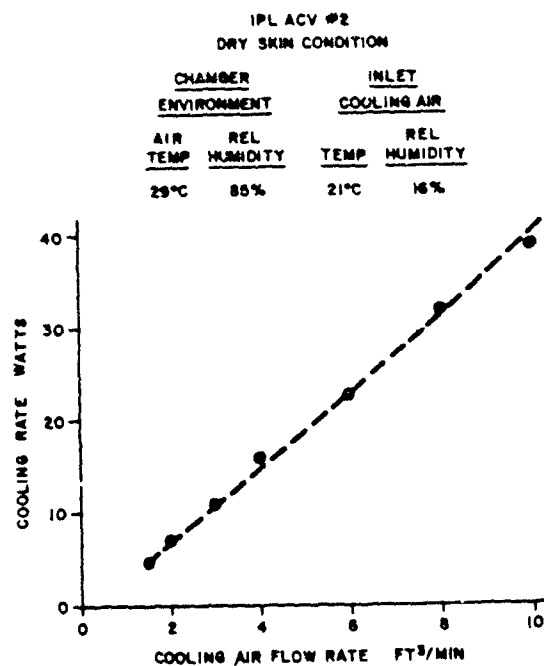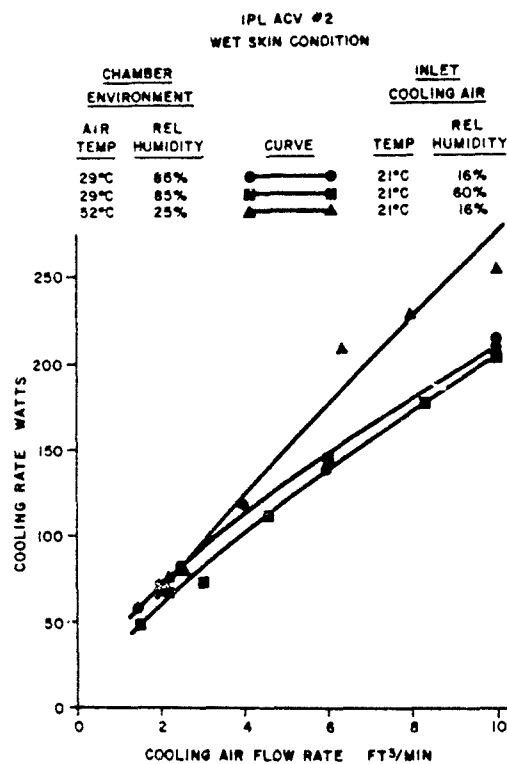COOLING AIR FLOW RATE   FT³/MIN

Figure 7.   Cooling rates (watts) provided by the IPL ACV #2 over the completely wet (maximal sweating) surface of the torso-arms-legs area as a function of the cooling air flow rate.

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F. Cooling Rates (Watts) Provided Over the Completely Wet (Maximal Sweating) Skin Surface of the Torso-Arms-Legs by the IPL ACV #2

The cooling rates (watts) provided by the IPL ACV #2 over the torso-arms-legs area are given in Table VI for two cooling air inlet conditions (21°C at 16% and 21°C at 60% relative humidity), two hot chamber environments (29°C at 85% relative humidity and 52°C at 25% relative humidity) and cooling air flows ranging from 1.5 to 10.0 ft^3/min. Cooling rate (watts) curves for each of the three chamber and inlet cooling air environmental conditions are plotted against the cooling air flow rate in Figure 7. Similar to the curves plotted in Figure 4, these cooling curves are dependent upon the particular hot environment in which exposure takes place. The two cooling curves for exposure to the hot environment of 29°C at 85% relative humidity are displaced from one another; the curve for inlet air humidity of 60% is displaced below the curve for inlet air humidity of 16%, showing a reduction in the cooling rate with increasing relative humidity of the inlet air. However, when the cooling efficiencies for these two relative humidity conditions are calculated, the inlet cooling air at the higher (i.e. 60%) relative humidity shows about a 15% greater efficiency. This finding suggests that for two inlet cooling air conditions of constant temperature but different moisture content (i.e. the relative humidity of one greater than the relative humidity of the other), the cooling efficiency of the one with the initially higher relative humidity will always be equal to (when both are moisture saturated) or greater than the cooling efficiency of the one with the lower relative humidity. The ventilating air with the higher relative humidity requires a shorter path over a completely wet (maximal sweating) skin surface before it reaches moisture saturation than ventilating air at a lower relative humidity. The cooling efficiency will be 100% if this ventilating air becomes saturated at skin temperature prior to its leaving the skin surface and exiting through the

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clothing to the hot environment. If this longer path required for the lower relative humidity ventilating air to reach saturation occurs partly within the clothing layers rather than strictly along the skin surface, then the cooling efficiency cannot be 100% even though the ventilating air leaves the clothing saturated at skin temperature. When comparing the cooling efficiencies of different air-cooled undergarments, not only the flow rate and temperature of the inlet cooling air have to be the same, but also its relative humidity. Although all three curves are grouped closely together at air flows of about 4 ft^3/min or less, the curve for a hot environment of 52°C and 25% relative humidity consistently shows higher cooling rate values than the others above 4 ft^3/min. Again, this is consistent with the findings in Figure 4 for the IPL ACV #1. Under the same cooling air flow rate, temperature and relative humidity, cooling provided by air supplied to these vests is greater in the higher air temperature environment; i.e., a given quantity of ventilating air is more efficient. For an inlet air temperature of 21°C and either 16% or 60% relative humidity, and exposure to 29°C air temperature at 85% relative humidity, most of the cooling provided by this air-cooled vest (IPL ACV #2) is over the torso. Less than 5% of the total cooling is provided over the arms and legs, up to a cooling air flow of about 5 ft^3/min. The contribution of the arms and legs increases to about 17% of the total cooling over the torso-arms-legs area at an air flow rate of 10 ft^3/min. For a hot environment of 52°C, 25% relative humidity, the contribution of the arms and legs increases to about 20% at an air flow of 6 ft^3/min. The cooling efficiency of this air-cooled vest (IPL ACV #2) for a completely wet (maximal sweating) skin condition is about 74% for ventilating air flows of 3 ft^3/min or less and 57% for ventilating air flows greater than 3 ft^3/min. This is about double the cooling efficiency of the IPL ACV #1. At these cooling air flows, a decrease in the flow rate results in an

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increase in cooling efficiency, but less cooling would be provided over the torso-arms-legs area at the lower cooling air flows.

G.   Comparison Between the Cooling Rates (Watts) Provided by the IPL ACV #1 and the Air-Cooled Vest #3 When Both Are Worn with the XM-29 Face Piece Over a Completely Wet (Maximal Sweating) Skin Surface

The Air-Cooled Vest #3 was studied under the same experimental conditions as the IPL ACV #1 given in Table IV.   Exposure was to two hot chamber environments (air temperature of $32^{\circ}C$ at 26% relative humidity, and $49^{\circ}C$ at 11% relative humidity) and ventilating air was supplied to both the Air-Cooled Vest #3 and the XM-29 Face Piece at either $24^{\circ}C$ at 41% relative humidity, $32^{\circ}C$ at 26% relative humidity or $43^{\circ}C$ at 14% relative humidity. Ventilating air flows ranged from 3 to 15 ft^3/min at the inlet of the Air-Cooled Vest #3 and were either 3 or 4.5 ft^3/min at the inlet of the XM-29 Face Piece. From the photograph shown in Figure 8 it can be seen that this vest is a harness type of undergarment that directs the ventilating air not only over the torso area but up the back of the neck and down the front and back of the legs.   The exit paths for the ventilating air consist of pin holes spaced along the coated fabric which makes up this vest.   The cooling rates (watts) and experimental conditions used in studying this vest are given in Table VII.

Comparing the cooling rates over the torso-arms-legs area in Table IV for the IPL ACV #1 with the cooling rates (watts) in Table VII for the Air-Cooled Vest #3 shows very little difference at the low ventilating air flows (3 or 6 ft^3/min); only about a 5% difference is noted.   At a ventilating flow rate of 10 ft^3/min the cooling rate for the Air-Cooled Vest #3 is about 50% greater than the cooling rate for the IPL ACV #1.   However, increasing the ventilating air flow to 15 ft^3/min reduces this percentage difference in the cooling rates to 12%.
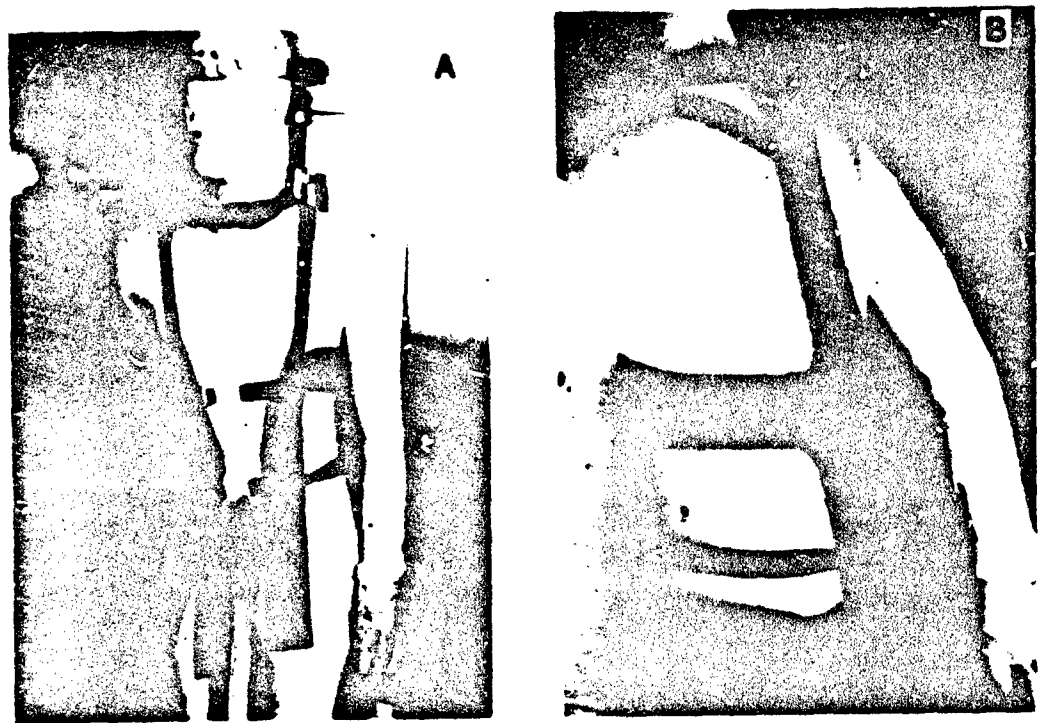
Figure 8.   Photographs of the Air-Cooled Vest #3: A. Front View, B. Back

View

TABLE VII

COOLING RATES (WATTS) PROVIDED BY THE AIR-COOLED VEST #3 WORN WITH A COOLING AIR VENTILATED XM-29 FACE PIECE

Completely Wet (Maximal Sweating) Skin Surface at 35°C

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY	FLOW RATE (FT³/MIN) AIR-COOLED VEST	XM-29 FACE PIECE	COOLING RATES			CHAMBER ENVIRONMENTAL CONDITIONS
			TORSO-ARMS-LEGS	HEAD	TOTAL***	
24°C at 41% RH*	3	3	42 (18.0)****	26 (8.7)****	68 (22.7)****	32°C at 26% RH*
32°C at 26% RH	6	3	73 (8.8)	39** (13.0)	92 (21.8)	32°C at 26% RH
32°C at 26% RH	15	6.5	159 (10.6)	36 (8.0)	195 (18.6)	49°C at 11% RH
43°C at 16% RH	10	3	113 (11.3)	21 (7.0)	134 (18.3)	49°C at 11% RH

* Relative Humidity
** Hood not worn over head
*** Sum of cooling provided over Head-Torso-Arms-Legs
**** Watts/Ft³/min

Considering the distribution in the cooling rate (watts) over the torso-arms-legs for the low ventilating air flows shows that about 92% of the cooling is provided over the torso for the Air-Cooled Vest #3 and only about 70% for the IPL ACV #1. At the higher ventilating air flows both air-cooled vests provided about 55% of their cooling over the torso. The Air-Cooled Vest #3 provides little or no cooling over the arms; only about 6% of the total cooling at the higher ventilating air flows. The contribution of the legs to the total cooling increases from about 8% at the lower ventilating air flows to 39% at the higher ventilating air flows. The IPL ACV #1 provides about 19% of its total cooling over the arms at the lower ventilating air flows which decreases to 13% at the higher ventilating air flows, with the contribution from the legs increasing from about 11% to 32%.

The cooling efficiency of the Air-Cooled Vest #3 is about 31% compared with 28% for the IPL ACV #1 under the four experimental conditions studied. The cooling efficiency of the ventilated XM-29 Face Piece is about 18% when worn with the IPL ACV #1 and 22% when worn with the air-cooled vest #3. The higher efficiency for the XM-29 Face Piece when worn with the Air-Cooled Vest #3 is probably the result of cooling air exiting at the back of the neck (under the hood) from the Air-Cooled Vest #3.

At the lower cooling air flow (3 ft^3/min), directing cooling air up the back of the neck (Air-Cooled Vest #3) results in a 13% increase in head cooling compared with the cooling rate for the head when the IPL ACV #1 is worn. Increasing the cooling air flow to these vests to 10 ft^3/min shows a 40% higher head cooling when the Air-Cooled Vest #3 is worn, compared with that for the IPL ACV #1. Further increasing the cooling air supplied to these vests to 15 ft^3 min, however, results in this percentage difference dropping to about 20%. Apparently at this high air flow, air exiting from the IPL ACV #1 up the top of

the torso is providing a measurable cooling air flow under the hood and over the head. This reduces the advantage noted for the Air-Cooled Vest #3 at the lower air flows, which was gained by directing cooling air up the back of the neck.

4. DISCUSSION

Cooling air supplied by an air-cooled undergarment has the potential of providing its maximum cooling, some cooling, or little or no cooling to the surface of a body. If all of this cooling air exits to the hot environment without passing over the skin surface, then little or no cooling will be provided. If all of this ventilating air passes over the skin surface and then exits to the hot environment saturated with moisture at the temperature of the skin, the ventilating air has provided maximum cooling to the body. The cooling air flow rate has to be sufficient to ensure that this ventilating air does not reach moisture saturation before it completes its passage over the skin, since warm, saturated air will not provide any cooling of surfaces over which it passes. The design of an air-cooled undergarment can play a significant role in determining how efficiently the cooling air supplied to the inlet of an air-cooled undergarment performs its function of cooling a body.

The original IPL Air-Cooled Undergarment, IPL ACV #1, was fabricated using a low resistance air space enclosed between moderately porous covers to diffuse the cooling air over the torso. Using this design, some of the cooling air has a tendency to exit the undergarment through the back covering and then through the clothing layers without passing over the surface of the skin. The newer model air-cooled undergarment, IPL ACV #2, utilizes a mesh type of covering which offers very low resistance to the passage of the cooling air. This type of covering diffuses the cooling air more readily, i.e., minimizes the formation of a stream of cooling air passing directly through one particular area

of the air-cooled undergarment covering and clothing to the hot environment. The Air-Cooled Vest #3 uses a highly air resistant coated fabric with pin holes spaced throughout its length to direct the cooling air, not only over the torso, but up the back of the head and down the legs. The cooling air leaving through the pinholes located on the end sections of this air-cooled undergarment does not initially flow over the torso where it could pick up heat and moisture. This design attempts to provide a broad diffusion of cooling air over the total surface of an air-cooled undergarment rather than a large stream of cooling air exiting over several small areas. However, since the cooling air exits this air-cooled undergarment through a number of pinholes, rather than a broad stream of cooling air, the quantity of cooling air available to diffuse over the arms was not significant at these ventilating air flows.

5. CONCLUSIONS

There is very little difference in the cooling rate (watts) between the IPL ACV #1 and the Air-Cooled Vest #3 at the lower cooling air flow rates. As this flow rate increases to 10 ft^3/min, the air-cooled vest #3 provides about 50% more cooling, but increasing the flow rate to 15 ft^3/min shows only about a 12% advantage. At the low cooling air flows about 92% of the cooling is provided over the torso for the Air-Cooled Vest #3 and only about 70% for the IPL ACV #1. At the higher cooling air flows this percentage decreases to about 55% for both air-cooled vests. The Air-Cooled Vest #3 provides very little cooling over the arms; cooling air exiting from this vest is primarily directed over the torso or down the legs.

The primary contributor to both the calculated maximum cooling potential values and the experimental cooling watts values is the cooling provided by the evaporative heat transfer from the completely wet (maximal sweating) skin

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surface to the ventilating air. This rate of evaporative heat transfer (cooling watts) is not uniform over the skin surface. The ventilating air with the higher relative humidity (constant air temperature and flow rate) requires a shorter path over a completely wet (maximal sweating) skin surface to reach moisture saturation than ventilating air at a lower relative humidity. Therefore, when comparing the cooling efficiencies of different air-cooled undergarments, not only the flow rate and temperature of the inlet cooling air have to be the same, but also its relative humidity.

The cooling rates (watts) provided by any of these three air-cooled vests or the ventilated XM-29 Face Piece for a completely wet (maximal sweating) skin surface are dependent not only upon their design but also upon the air temperature, relative humidity and flow rate of the ventilating air, plus the air temperature and relative humidity of the hot environment. In a hot environment of 49°C at 11% relative humidity and ventilating air at a temperature of 32°C at 26% relative humidity, for a ventilating air flow of 15 ft^3/min the cooling rate is 142 watts for the IPL ACV #1 and 159 watts for the Air-Cooled Vest #3. At a ventilating flow rate of 4.5 ft^3/min the cooling rate (watts) for the head would be about 33 watts $\pm$ 10%. For a hot environment of 29°C at 85% relative humidity, the cooling rate (watts) for the IPL ACV #1 was 137 watts versus 212 watts for the IPL ACV #2 at an inlet air flow rate of 10 ft^3/min, and a temperature of 21°C (10% relative humidity for the IPL ACV #1 and 16% for the IPL ACV #2).

6. FUTURE STUDY PLANS

The Biophysics Branch, Military Ergonomics Division has initiated and is continuing a systematic program for the assessment of various types of auxiliary cooling undergarments prior to human, physiological studies in a hot chamber and/or natural environment. These sectional manikin studies investigating the cooling benefits provided by auxiliary cooling undergarments provide direct measurements of the cooling rates (watts) for continuously supplied and controlled cooling air or water. These fluids are supplied to an undergarment through an umbilical connection connected to a heat exchanger. Portable auxiliary cooling undergarments which do not require any umbilical connections to a heat exchanger have also been studied. A report describing the heat transfer properties of an ice packets vest containing up to 91 ice packets has already been published (2). Another study using a vest containing fluid which is cooled in a portable heat exchanger containing ice or frozen canisters and forced through the tubing of the undergarment by a pump operating off of a battery has been completed. The final technical report of this series will discuss this study.

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